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FIRST QUARTERLY REPORT

ON

BONDING LARGE AREA SILICON WAFI

CONTRACT NO. 952022

PREPARED FOR

JET PROPULSION LABORATORY
4800 Oak Grove Drive
Pasadena, California 91103

PREPARED BY

MOTOROLA, INC.
SEMICONDUCTOR PRODUCTS DIVISION
5005 E. McDowell Road
Phoenix, Arizona 85008

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ABSTRACT

Results are presented on the first three months study of an eighteen month program for bonding large area silicon single crystals to heat sinks. Both gold-silicon alloy and aluminum-germanium alloy solder systems have received preliminary evaluations. Computer programs are being written for a study of stresses set up between bonded materials due to differences in their thermal expansion coefficients and a study of heat flow from dissipating junctions to the package heat sink. A thermal conductometer has been selected and ordered to enable the thermal conductivities of solder alloys to be determined as a function of their composition.

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1.0 INTRODUCTION

This report describes work done during the first three months of an eighteen month program on a study for reliabily bonding large area silicon single crystals to suitable heat sinks. The purpose to determine a method for bonding silicon single crystals greater than 10,000 square mils and approaching two inches in diameter to excellent heat sinks in a manner which does not damage the silicon or alter the electrical properties of semiconductor devices constructed therein. The system should not degrade under repeated thermal shock. The technique is to be applied to the packaging of large scale integrated circuit devices.

Phase one of this program is a study of the basic properties of bonding material and techniques which will determine the materials and processes to be utilized for early large area bonding experiments.

Preliminary studies are reported on the use of gold-silicon and aluminum-germanium bonding alloys.

A theoretical analysis for computer solution is being developed to study strains which are set up at bonded interfaces due to the disparity in the coefficient of thermal expansion. This is of particular importance since silicon possesses one of the lowest expansion coefficients. This study will provide much needed information concerning the selection of materials and their dimensions such as the minimum silicon thickness, the minimum thickness for a stress relieving member placed between the package heat sink and silicon, and the mechanical properties of bonding solders.

A program is also being set up for computer solution concerning heat flow from power dissipating junctions to the package heat sink. Coupled with this program is a study which will be initiated on the thermal conductivity of various potential solder alloys as a function of their composition. The equipment to be used for this study is briefly described.

2.0 TECHNICAL DISCUSSION

2.1 GOLD-SILICON ALLOY SOLDER TO MOLYBDENUM

A standard solder for bonding silicon is a gold-silicon alloy whose composition is close to that of the eutectic. The eutectic composition melts at a convenient 370°C which is sufficiently high to enable device stress testing but also is not excessive to damage the circuit during bonding.

Typically the silicon wafers are back-etched in a hydrofluoric acid solution to remove the natural oxide which exists on the silicon. The wafers are then immediately placed into a vacuum ambient where a gold film is deposited on the silicon by evaporation techniques. The silicon with the gold backing is then heated to a few degrees above the gold-silicon eutectic temperature where the gold and silicon melt to form the eutectic solder at about 6 percent by weight of silicon. In the process nearly 1 micron of silicon is consumed for each 2 microns of gold film.

During this report period, a study was initiated to evaluate the use of gold-silicon eutectic for bonding 1-inch-diameter silicon wafers to gold plated molybdenum substrates. Because the eutectic solder formed by the above described techniques consists of silicon crystallites dispersed through a gold matrix, some of the silicon appears at the surface of the solder where it forms

a thin coat of SiO_2 over the exposed crystallites. To eliminate the silicon dioxide, which would possibly interfere with the soldering operation, the oxide and all exposed surface crystallites of silicon were etched away with 19 parts by volume of nitric acid (70% reagent grade) and 1 part by volume of hydrofluoric acid (49% reagent grade). This treatment leaves a silicon and silicon dioxide free surface of gold covering the solder.

One-inch-diameter, 6-mil-thick silicon wafers with gold-silicon eutectic solder backing were then placed onto gold plated 1/16-inch molybdenum plate and the assembly was fired in nitrogen at 420°C. The wafers were attached firmly to the molybdenum; however, inspection of the edge of the silicon by microscopic techniques indicated that the solder did not completely wet out to the edge to form an anticipated fillet.

Further work will be carried out to determine proper bonding conditions. It was gratifying that none of the silicon wafers brazed down by this manner fractured.

2.2 ALUMINUM-GERMANIUM BONDING ALLOY

It is desirable because of its low density (and recently from cost considerations) to utilize an aluminum mass rather than copper as the final package heat sink. One major problem which arises with the use of aluminum is its difficulty to accept solder because of a thin layer of aluminum oxide which forms on the sluminum surface. A program has been initiated to study the use of an aluminum-germanium eutectic solder for bonding silicon directly to an aluminum header. The solder is also of interest because it promises to possess a high thermal conductivity and could advantageously be used to bond silicon to a stress relieving member or the member to aluminum.

A technique has been devised during this report period for depositing aluminum and germanium on the back side of silicon wafers which when heated forms an alloy richer in germanium than is the eutectic of 54% germanium by weight. Silicon die coated with such a layer forms a good bond to aluminum or aluminum coated nickel or to aluminum coated Kovar alloy when brazed at 440°C. Good bonds are also made to molybdenum if the eutectic composition of the alloy is used for the solder.

The process which has been developed is as follows:

(1) Back etch silicon wafers in HF
(2) Evaporate a 1.5-micron-thick layer of aluminum on the silicon at 200°C substrate temperature.
(3) While in the vacuum cool the substrate to room temperature or below and deposit a 1.5-micron thick germanium film.
(4) Bond to aluminum or aluminum coated metal in N_2 or forming gas at 435°C.

The composition of the evaporated solder with the above specified thicknesses is 66 percent germanium and 34 percent aluminum by weight. This compares to the composition of the eutectic of 54 percent germanium by weight. The extra germanium in this solder is available to combine with the aluminum substrate at the eutectic temperature of 424°C to form additional eutectic alloy thus promoting the flow and wetting of the solder to the aluminum. In the process some of the substrate is consumed to form additional melt. The bonding temperature in excess of 424°C also aids in the formation of additional solder with the excess aluminum available from the substrate. At this temprature an alloy forms which is richer in aluminum than is the eutectic. Theoretically, at 435°C with excess aluminum available from the substrate, a 52-percent by weight germanium solder can form.

Adherence of the solder is promoted by the fact that aluminum can form a solid solution to a slight extent with silicon and molybdenum while germanium is slightly soluble in aluminum.

The layered structure of the alloy componenets as deposited on the silicon enables the alloy to form during the bonding operation. With the germanium sandwiched between aluminum surfaces during the bonding operation, it is free to dissolve some of the substrate as well as the deposited aluminum. This action further promotes adhesion.

Additional evaluations of aluminum-germanium solder will be made during the course of this program.

2.3 THERMOCONDUCTIVITY MEASUREMENTS

It is important to determine accurately the thermoconductivity of the various elements which comprise the thermal path to the heat sink to enable a good thermal design for the package. Of great importance is an understanding of the thermal conductivity of the various solder alloys which may be used between the silicon and on intermediate pad or between the pad and the heat sinking stud since this information is generally not available.

Motorola has purchased a thermal conductometer manufactured by Colora Messtecknik G.m.b.H. of Germany to enable an accurate determination ($\pm$ 3%) of the thermal conductivity of potential package materials. A description of the instrument is given in the Review of Scientific Instruments, Vol. 34, No. 6, pp. 615-621, June 1963. The thermal conductometer is based upon a steady state measurement of thermal flow determined by the rate of liquid evaporation due to the thermal flow. The rate of liquid evaporation is compared to a graph which is previously determined by means of calibrated samples.

The equipment has been ordered but has not yet been received. Plans are being made, however, to measure the thermal conductivity of various solder alloys with their composition as a variable. It should also be possible to determine the thermal conductivity of various interfaces bonded by solders.

2.4 HEAT CONDUCTION ANALYSIS

An analysis of thermal conduction for this large area bonding study is being made for programming a GE 415 time sharing computer which is available to Motorola. A model using cylindrical coordinates is considered involving silicon substrates bonded to a stress relieving metal which in turn is bonded to a copper or aluminum heat sink study.

The general equation to be solved in dimensionless form is:

$$\frac{\partial t}{\partial \phi} = \frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r} + \frac{\partial^2 t}{\partial Z^2} + \omega$$

where t = temperature in degrees centigrade

ϕ = dimensionless time = $\frac{C_p \rho R^2}{k}$ ϕ_{real}

r = dimensionless distance in the r direction

= $\frac{r_{real}}{R}$

Z = dimensionless distance in Z direction

= $\frac{Z_{real}}{R}$

ω = heat generation term in degrees centigrate

= $\frac{\omega_{real}\, k}{R^2}$

R = radius

k = thermal conductivity

C_p = heat capacity

f = density

The dimensions of ω_{real} are cal/cm^3 sec

The boundary conditions which apply are:

(1) at the center $q = k \left(\frac{\partial t}{\partial r}\right)_{r = o} = 0$

(2) at the edge $q = k \left(\frac{\partial t}{\partial r}\right)_{r = R} = 0$

(3) at the top of the silicon

$$q = k \left(\frac{\partial t}{\partial Z}\right)_{Z = top} = 0$$

(4) at the interfaces between materials

$$q_1 = q_2$$

$$k_1 \left(\frac{\partial t}{\partial Z}\right)_1 = k_2 \left(\frac{\partial t}{\partial Z}\right)_2$$

where the subscripts represent different materials

(5) the temperature at the base of the heat sink (copper or aluminum) is a constant T_o

(6) the generation term will be zero for all materials but the material at the junction

Two problems can be solved. The steady state temperature distribution

$$\left(\frac{\partial t}{\partial \phi}\right) = 0, \ \omega = \text{constant}$$

and the unsteady state

$$\left(\frac{\partial t}{\partial \phi}\right) = 0 \text{ and } \omega = f(\phi)$$

The numerical solution equation (forward differences) takes the form

$$t_5 = t_o \left[1-2P \left(\frac{1}{h^2} + \frac{1}{m^2}\right)\right] + t_3 \; P \left(\frac{1}{h^2} - \frac{1}{2hr}\right)$$

$$+t_4 \; P \left(\frac{1}{h^2} + \frac{1}{2hr}\right) + (t_1+t_2) \left(\frac{P}{m^2}\right) + Pw$$

where t_o, t_1, t_2, t_3, t_4, h and m are grid points and dimensions illustrated in Figure 1.

t_5 is the temperature at point "0" at a time interval P in the future.

To obtain a stable solution

$1 - 2 P \left(\frac{1}{h^2} + \frac{1}{m^2}\right)$ must be equal to or greater than zero

$$P_{max} = \frac{1}{2\left(\frac{1}{h^2} + \frac{1}{m^2}\right)}$$

If the grid spacing has to be made very small (as for the junction), the largest time step allowed is too small for the computer solution within a reasonable length of solution time. To avoid this backward difference, formulations are used for computing the junction temperature with the form

$$t_o \left[1+2 \; P \left(\frac{1}{h^2} + \frac{1}{m^2}\right)\right] = t_5 + t_3 \left(\frac{1}{h^2} - \frac{1}{2hr}\right)$$

$$+t_4 \left(\frac{1}{h^2} + \frac{1}{2hr}\right) + (t_1 + t_2) \; \frac{P}{m^2} + Pw$$

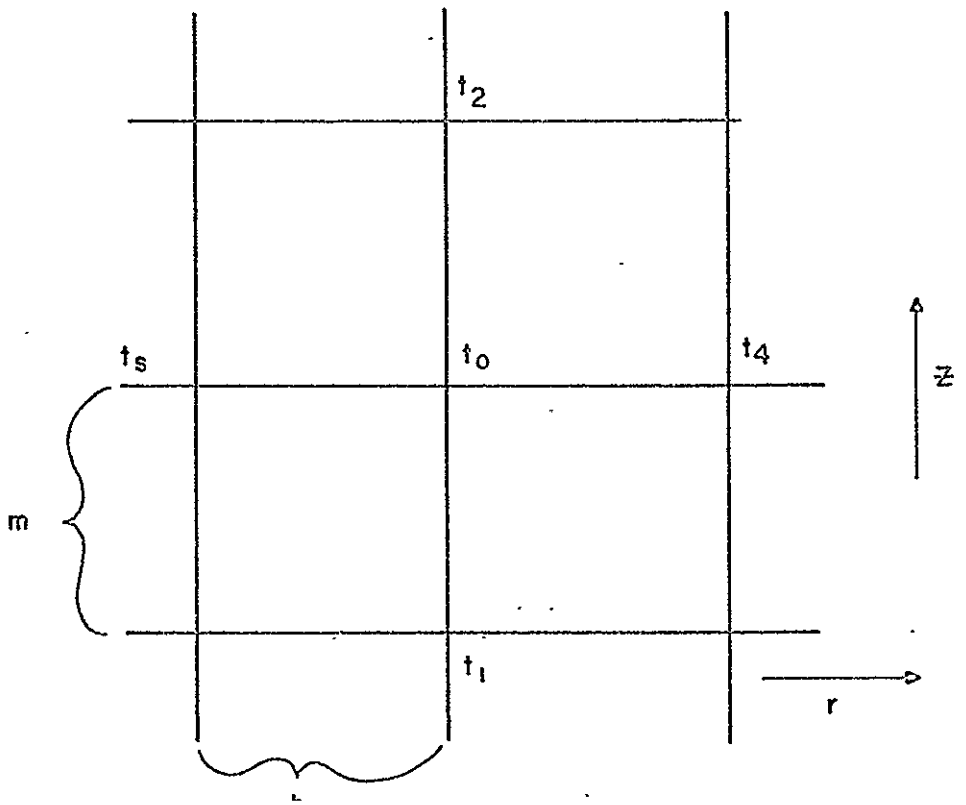

Figure 1. Grid for Numerical Solution of Cylindrical Heat Flow Problem

In this case t_5 is the present point and t_o, t_1, t_2, t_3, are all future points.

The matrix of these points are solved by the determinate method and a larger grid spacing is used for the points outside of the junction region.

The solution will be put on the computer located in the Motorola Semiconductor Products Division plant.

2.5 STRESS ANALYSIS

A computer study is being set up to study the stress generated at large area bonds due to the difference in coefficient of thermal expansion between two joining materials. The intent is to determine the extent of these stresses and how they fall off with distance along the Z axis. This will enable the calculation of the minimum thickness of a stress relieving material placed between the silicon wafer and the main device heat sink. The use of a minimum thickness stress relieving material will optimize the thermal conductivity between the silicon and the device main heat sink. The analysis method to be employed requires a solution of the displacement problem and then a determination of the stresses are made from the displacements.

The stresses in terms of the displacements for the plane strain problem are:

$$\sigma x = \frac{E\ (1-\nu)}{(1+\nu)(1-2\nu)} \left[\frac{\partial u}{\partial x} + \frac{\nu}{1-\nu} \frac{\partial v}{\partial y} - \frac{(1+\nu)}{(1-\nu)} kT \right]$$

$$\sigma y = \frac{E\ (1-\nu)}{(1+\nu)(1-2\nu)} \left[\frac{\partial v}{\partial y} + \nu \frac{\partial u}{\partial x} - \frac{(1+\nu)}{(1-\nu)} kT \right] \qquad (1)$$

$$Txy = \frac{E}{2(1+\nu)} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)$$

where u = displacement in the x direction
v = displacement in the y direction
σ, τ = stresses
E = modified Youngs modulus for plane strain
ν = elastic constant
k = thermal coefficient of linear displacement
T = temperature change

The differential equations to be solved are:

$$\frac{(1-\nu)}{(1-2\nu)}\frac{\partial^2 v}{\partial x^2}+\frac{1}{2\ (1-2\nu)}\frac{\partial^2 v}{\partial y^2}+\frac{1}{2}\frac{\partial^2 v}{\partial x\partial y}=0$$

$$\frac{(1-\nu)}{(1-2\nu)}\frac{\partial^2 v}{\partial y^2}+\frac{1}{2(1-2\nu)}\frac{\partial^2 v}{\partial x^2}+\frac{1}{2}\frac{\partial^2 v}{\partial x\partial y}=0 \qquad (2)$$

The numerical forms of equations (1) are used to determine u and v in the main body of the material. Special equations must be developed for the points along the planes, a, b, c, d, e and f (see Figure 2) from boundary conditions, interface conditions and assumptions.

It is assumed there will be no ridged body motion and the point (a,e) will be used as a reference. Therefore:

$$U_E = V_a = 0$$

V_E values are determined from symmetry. The side points V_F and U_F are determined by the boundary conditions

$$\sigma_x = \tau_{xy} = 0$$

The end points U_a, U_d, V_d are determined from the boundary conditions

$$\sigma_y = \tau_{xy} = 0$$

The interface points U_B, V_B, U_C, V_C are determined from the interface conditions

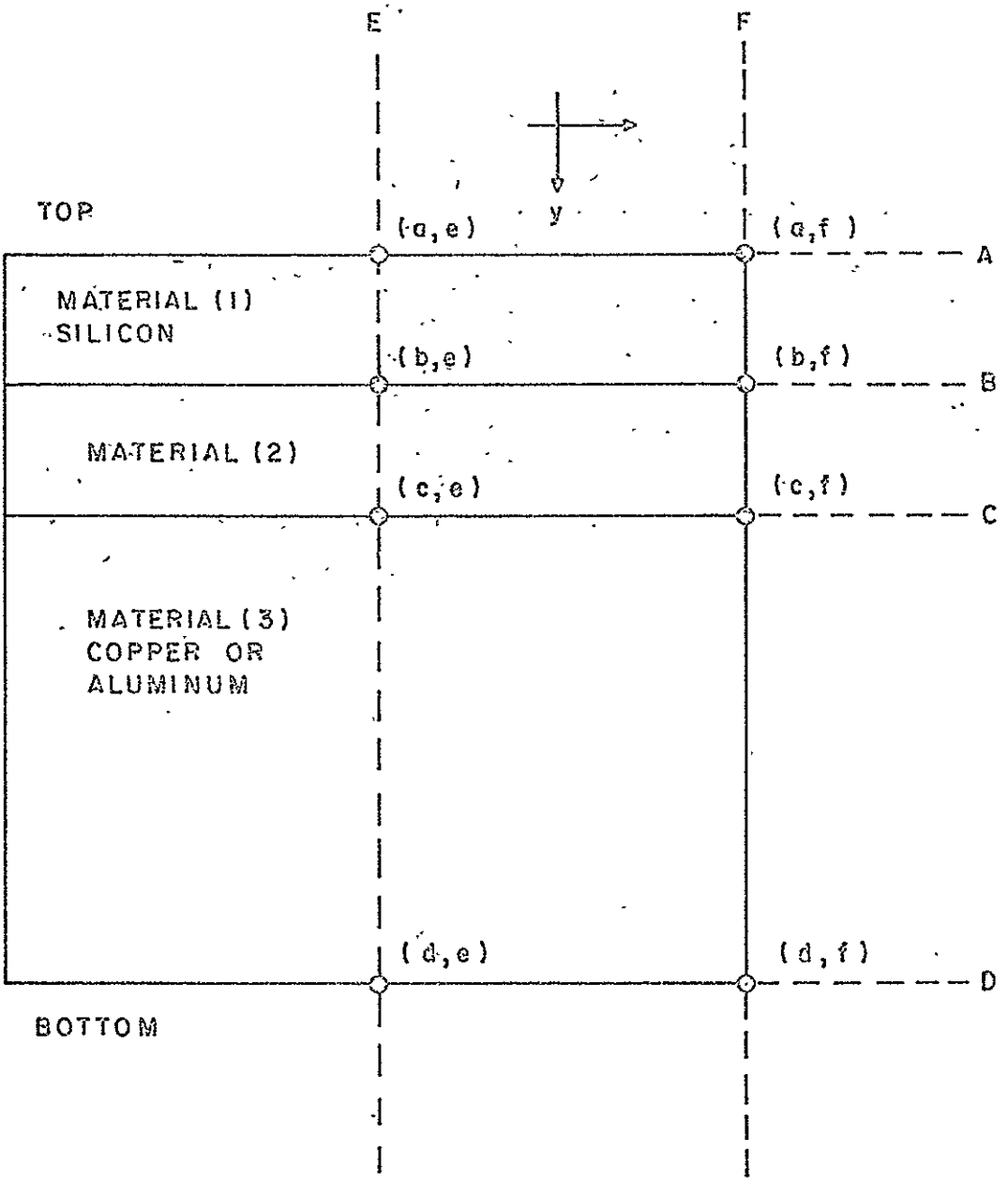

Figure 2. Stress Analysis Model

$U_i = U_j$ where i and j are adjacent materials

$V_i = V_j$

$T_{yi} = \sigma_{y_j}$

$xyi = \tau_{xy_j}$

Combinations of the conditions are used to determine the numerical equations at the intersections of the lines. Special caution must be exercised when determining the equations for points (a,f), (b,f), (c,f) and (d,f) where an oversimplification will result in an erroneous solution.

The equation will be programmed and displacements calculated for various thicknesses. The stresses will then be calculated from the displacements.

3.0 CONCLUSIONS

Two solder alloys have been briefly evaluated and will be the subject of further study for bonding large area silicon single crystals to heat sinks. The aluminum-germanium system is of particular interest since it is capable of wetting to aluminum.

A program is being prepared for computer analysis of stresses at bonded interfaces due to differences in the member thermal expansion coefficients. Also a program is being written for a computer study of heat flow from power dissipating junctions to package thermal sinks. These two programs will provide much needed information on the selection of materials and their dimensions

A thermal conductometer has been selected and ordered which will enable the generation of required information on the thermal conductivities of solder alloys as well as other potential package materials.

4.0 NEW TECHNOLOGY

No reportable items of new technology have been developed under this contract.

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